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High Temperature Mechanical Properties of HFIR Irradiated FeCrAl Alloys

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SUMMARY

Due to their excellent performance in high temperature oxidizing steam environments, Iron-Chromium-Aluminum (FeCrAl) alloys are a strong candidate material for Accident Tolerant Fuel (ATF) cladding applications. A number of these alloys, GenI FeCrAl alloys with varying Cr (10-18 wt. %) and Al (3-5 wt. %) content, irradiated to 7dpa at 320°C in the High Flux Isotope Reactor (HFIR), were tested in tension at 500 ºC, to add to previous data collected at room temperature and 250°C. A second group of GenII FeCrAl alloy controls, with 6 wt. %Al, and 10 to 13 wt. % Cr, were also tested in tension to use as baseline tensile data for ongoing irradiation experiments in HFIR.

MECHANICAL PROPERTIES OF HFIR IRRADIATED FeCrAl ALLOYS

1. INTRODUCTION

Due to the Fukishima accident of 2011 interest in accident tolerant fuels and cladding materials have increased. Research into claddings that are resistant to high temperature steam oxidation conditions seen in loss of coolant accidents (LOCA) have led to an interest in Iron-Chromium-Aluminum (FeCrAl) alloys, which form a protective aluminum oxide layer under these conditions. Irradiations of these alloys are underway in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). Alloys of various Cr content are being studied to understand the effects of irradiation produced Cr rich α' phase on the mechanical properties of these alloys. This report presents mechanical testing on four first generation (GenI) FeCrAl alloys of varying Cr (10-18 wt. %) and Al (3-5 wt. %) content that were irradiated to 7 dpa at 320°C in the HFIR reactor, as well as control samples of two second generation (GenII) FeCrAl alloys of varying Cr content (10 and 13 wt. %) that will be used for comparison to samples that are currently being irradiated in the HFIR reactor. This is an updated report of: T.A. Saleh, et al. "Mechanical Properties of HFIR Irradiated FeCrAl Alloys", LA-UR-17-28992, NTRD-FUEL-2017-000006, 9/20/2017. Fuller microstructure details are in this previous publication.

2. Alloys

The irradiated samples tested in this study were from the FCAY irradiation in HFIR, details of irradiation capsule and alloy choice are detailed in reference [1]. While there were a number of irradiation temperatures and doses in this irradiation, the samples tested here were from the 320°C and 7 dpa condition. The composition of these GenI FeCrAl alloys F1C5AY, B125Y, B154Y-2 and B183Y-2 are seen in Table 1. Notably Cr and Al content varies for each sample.

Table 1. Composition of FeCrAl alloys in this study

Alloy					Composition	(wt %)					
	Fe	**Cr**	**Al**	**Y**	**C**	**S**	**O**	**N**	**P**	**Si**	**Mo**
F1C5AY	85.15	10.01	4.78	0.038	0.005	0.001	0.0013	0.0003	0.006	<0.01	<0.01
B125Y	83.56	11.96	4.42	0.027	0.005	0.0013	0.0017	0.0009	0	0.01	<0.01
B154Y-2	80.99	15.03	3.92	0.035	0.005	0.0004	0.0025	0.0007	<0.002	0.01	<0.01
B183Y-2	79.52	17.51	2.93	0.017	0.005	0.0006	0.0015	0.0011	<0.002	<0.01	<0.01
C06M	81.8	10.03	6	0.01	0.003	0.0012	0.0016	0.0004	0.003	0.18	1.96
C36M	78.8	12.98	6	0.04	0.003	<0.0003	0.0016	0.0002	<0.002	0.18	1.98

Composition of GenII FeCrAl control materials C06M and C36M can also be seen in Table one. The tests on these alloys will serve as baseline for the future tests on the FCAT and FCAB irradiations currently in HFIR [2]. These samples are at a fixed Al composition of 6 wt.% and have 10 and 13 wt. % Cr. These samples were machined from wrought plates. The plates were processed as follows, based on optimized thermo-mechanical treatment detailed in reference [3]:

1. Vacuum induction melt
2. 1200°C anneal for 1 hr
3. 43% reduction via hot forging @1200°C followed by post deformation anneal
4. 50% reduction via hot rolling @ 800°C followed by post deformation anneal
5. 80% reduction via warm rolling @ 300°C to a final thickness of .08 in.
6. Post deformation anneal at 650°C for 1 hr followed by air cooling

Samples designated “B” were cut with the tensile axis aligned with the rolling direction. Samples designated “A” were cut with the tensile axis perpendicular to the rolling direction.

3. Tensile Testing

Tensile samples of the SS-J2 (S1) sample geometry (Figure 1) were tested on a 30 kN capacity Instron 5567 screw driven load frame located inside a hot cell in Wing 9 at the CMR facility at Los Alamos National Laboratory (Figure 2). The load frame is outfitted with an inert atmosphere furnace operable to 700 °C. Samples were loaded using manipulators into a set of ball ended grips in a shoulder loaded tensile fixture (Figure 3). Tests were performed at a constant cross head velocity of 0.3 mm/minute corresponding to a nominal engineering strain rate of 10^{-3} /sec. Load/displacement data were converted to engineering stress/strain data using the initial measured specimen dimensions. The compliance from the test system was mathematically removed from each curve. Elevated temperature tests were performed in an argon environment.

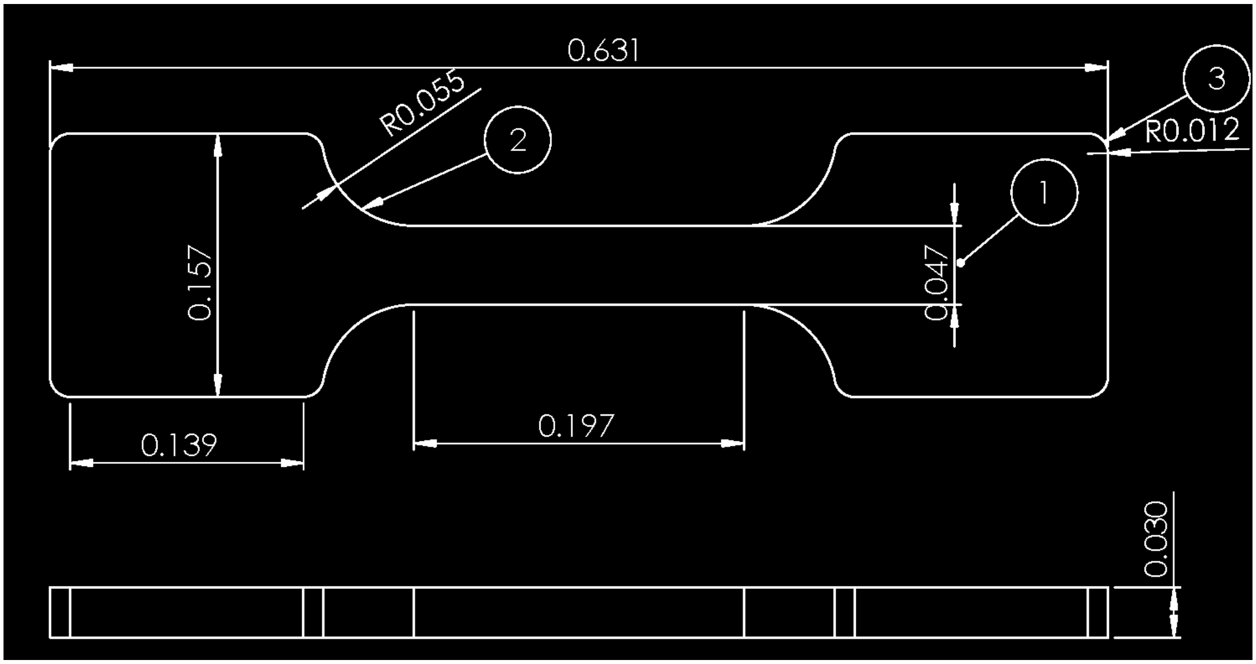

Figure 1 *Geometry of SS-J2 (S-1) tensile specimen. Dimensions in inches. Sample thickness varied from .020" to .030" for these experiments.*

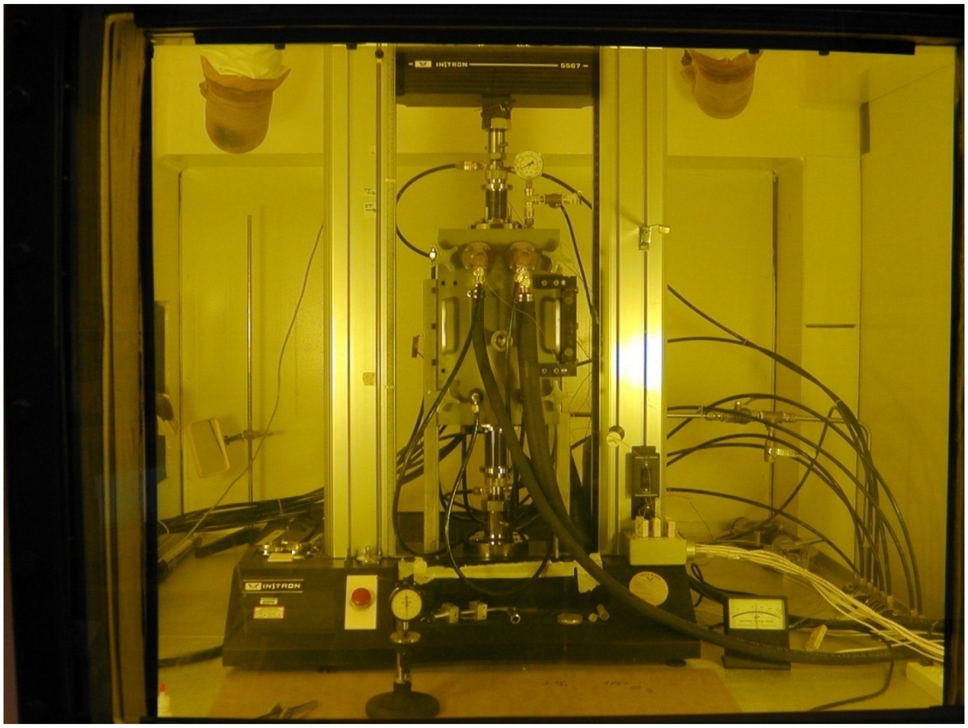

Figure 2 *Instron 5567 Load Frame, located in a hot cell at the CMR facility.*

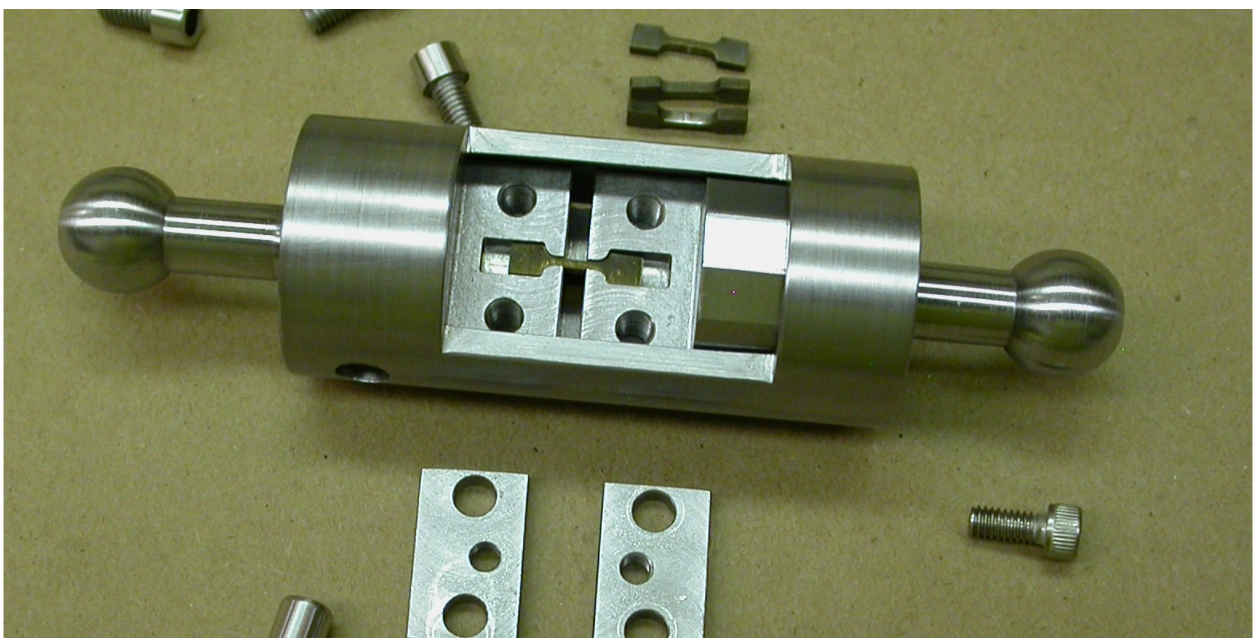

Figure 3 - *Ball end grips for shoulder loading samples.*

4. Tensile Results

A summary of all data collected for this report can be seen in Table 2. Data in red is where the uniform elongation was less than the 0.2% offset yield point, leading to the yield being calculated from a point after the UTS. There were no controls available for sample B183Y-2. One of the irradiated samples for this alloy was missing most of one of its grip sections, thus it was unable to be tested. This sample will be saved for future shear punch measurements. Generally, the GenI data is very consistent with previous irradiated tensile tests from the same irradiation [1,4], and the GenII data is consistent with tensile tests on samples cut from tubes [5]. Under these irradiation conditions, the GenI materials show little uniform elongation in all test temperatures at or below the irradiation temperatures.

Table 2. Summary of tensile testing data of the FeCrAl alloys in the HFIR irradiations.

Material	Sample	Tirr °C	dose (dpa)	Test Temp °C	Yield	UTS	UE%	TE%
F1C5AY	522	320	7	RT	775	775.0	0.3	7.9
F1C5AY	535	Control	Control	250	540	556.2	0.75	8.1
F1C5AY	523	320	7	250	685	694.3	0.08	5.6
F1C5AY	524	320	7	500	385	409.5	1.1	16.5
B125Y	2522	320	7	RT	830	833.4	0.25	6
B125Y	2535	Control	Control	250	510	521.2	0.4	7.1
B125Y	2523	320	7	250	700	701.4	0.16	5.8
B125Y	2524	320	7	500	450	456.9	0.9	24.5
B154Y-2	5422	320	7	RT	840	840.2	0.2	7.2
B154Y-2	5435	Control	Control	250	530	545.5	0.47	8.5
B154Y-2	5423	320	7	250	685	692.0	0.12	6.1
B154Y-2	5424	320	7	500	430	438.3	1	15.5
B183Y-2	8321	320	7	250	770	772.6	0.16	6
B183Y-2	8319	320	7	RT	-	-	-	-
B183Y-2	8322	320	7	500	515	520.9	0.5	12.5
C06M	A-1	Control	Control	RT	760	791.6	4.2	11.2
C06M	B-1	Control	Control	RT	740	798.5	7.8	17.1
C06M	A-2	Control	Control	250	640	703.6	4.6	11.2
C06M	B-2	Control	Control	250	620	731.0	7.2	13.5
C36M3	A-1	Control	Control	RT	760	793.0	5.1	11.7
C36M3	B-3	Control	Control	RT	755	816.9	8.1	19
C36M3	A-2	Control	Control	250	610	686.3	5.2	8
C36M3	B-2	Control	Control	250	610	734.0	7.1	
C36M3	A3	Control	Control	500	580	618	2	20.4

Figure 4 shows the stress strain curves for all GenI materials tested for this report. Figure 5 shows all the irradiated samples, without controls, at full scale. There are few obvious differences between alloys. Generally, the irradiated room temperature tests have the most hardening. The irradiated 250°C tests have the least ductility, and the irradiated samples tested at 500 °C have the most ductility and the lowest yields. There are no consistent trends with respect to alloy content, except for the hardening seen in the B183Y-2 tests at 250 and 500 °C. Control specimens were in short supply and no additional control curves are available from this round of tests.

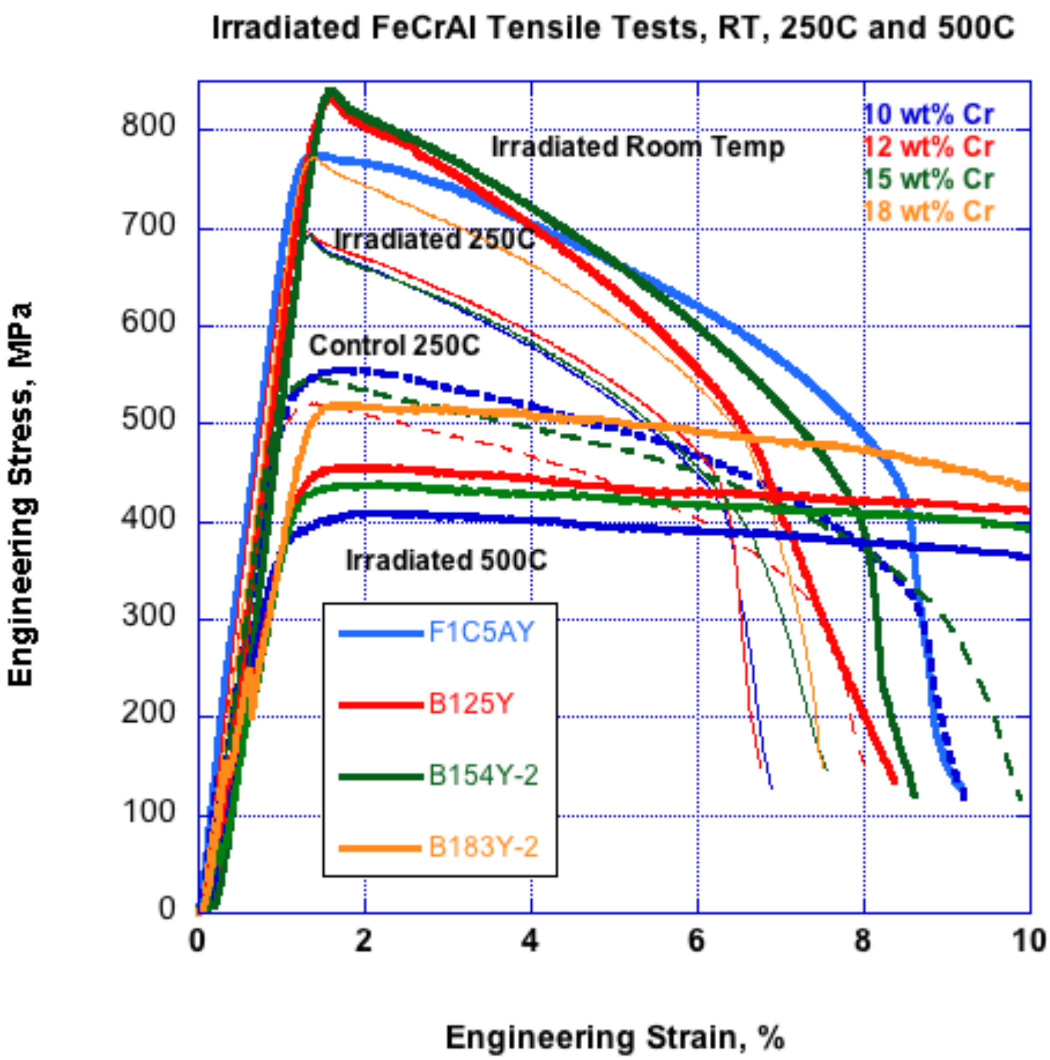

Figure 4 *All Tensile Tests for GenI FeCrAl alloys at Room Temperature, 250°C and 500°C*

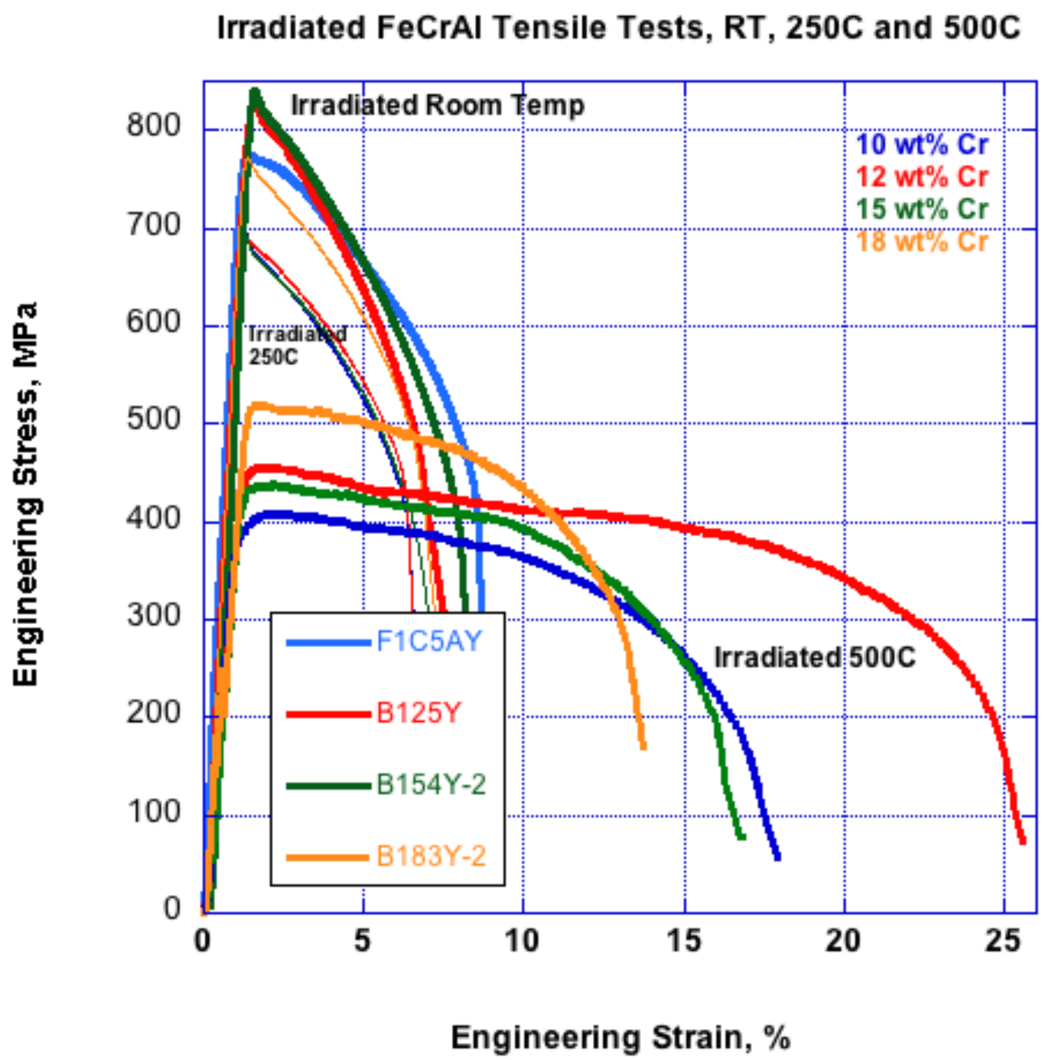

Figure 5 *All Tensile Tests for GenI FeCrAl alloys at Room Temperature, 250°C and 500°C, without the controls.*

Close ups of each test condition can be seen in figures 6, 7, 8 and 9. It is more evident in the irradiated condition specimens tested at room temperature, Figure 6, that F1C5AY (10%Cr) has less hardening when compared to the control tests (Figure 7), and slightly more ductility than the higher Cr alloys, this is likely due to lower amounts of α' forming in this alloy due to the lower Cr. This trend is not seen in the irradiated GenI specimens tested at 250°C, Figure 8. But here the B183Y-2 sample shows a much higher yield strength presumably due to more α' ingrowth due to the higher Cr, 18wt. %. There were no samples of this alloy available for 250°C control or irradiated room temperature test, however, some of these tests were done as part of previous studies [1,4], and it is clear the yield for this alloy is also higher on the room temperature tests of irradiated materials, while the control material tested at room temperature has the lowest yield strength compared to the other GenI alloys. Thus, the hardening is by far the highest for this 18%Cr B183Y-2 alloy. Similarly, (Figure 9), the 18%Cr B183Y-2 displays the most hardening, even though the ductility is much higher across the board due to a test temperature, 500°C, higher than the irradiation temperature of 320°C.

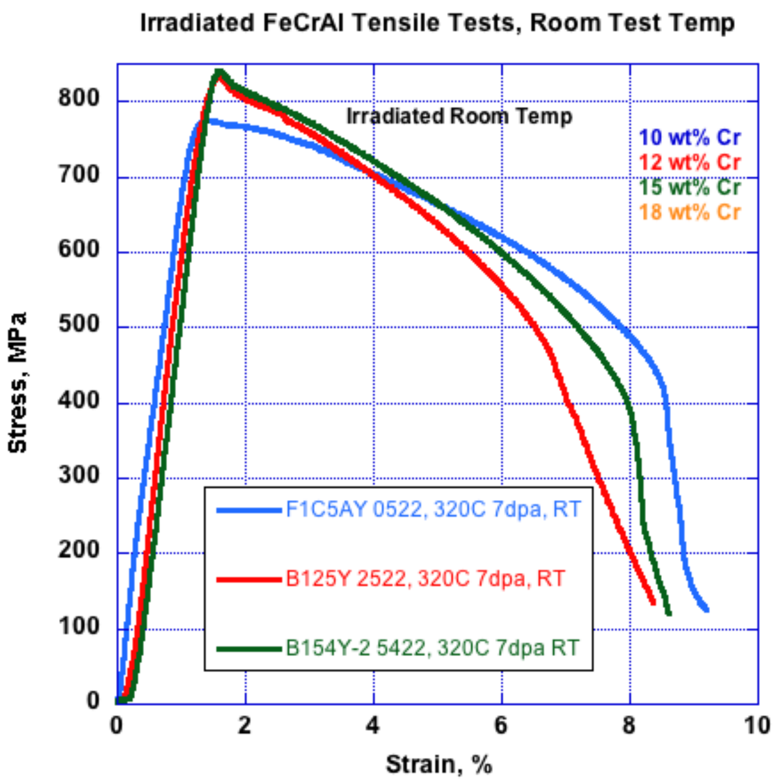

Figure 6 *Room temperature tensile tests of irradiated (320℃ 7dpa) GenI FeCrAl alloys.*

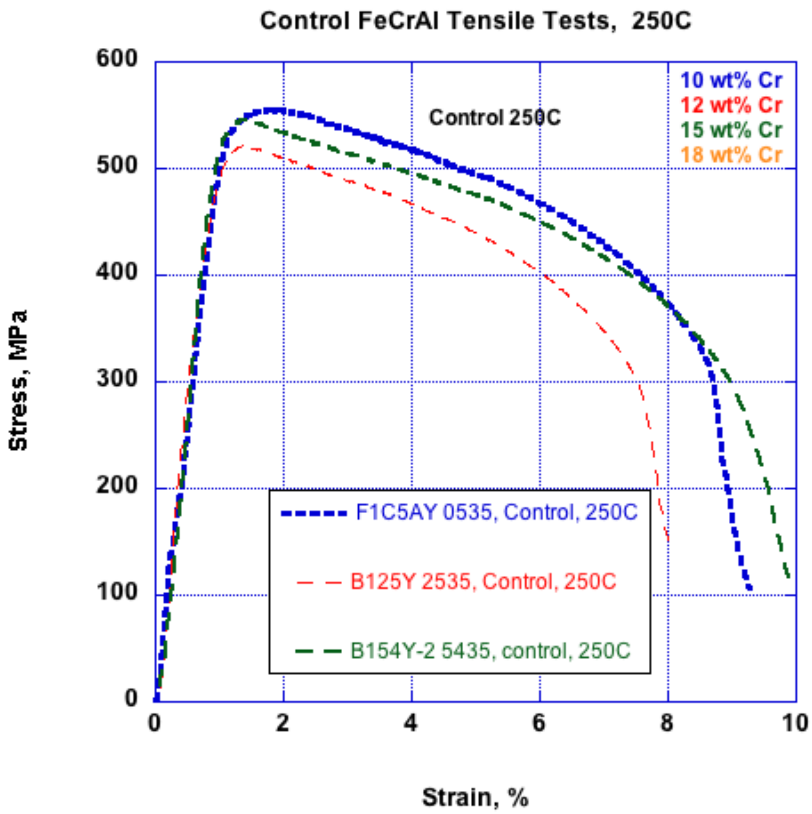

Figure 7 *Elevated (250℃) temperature tensile tests of control material for GenI FeCrAl alloys.*

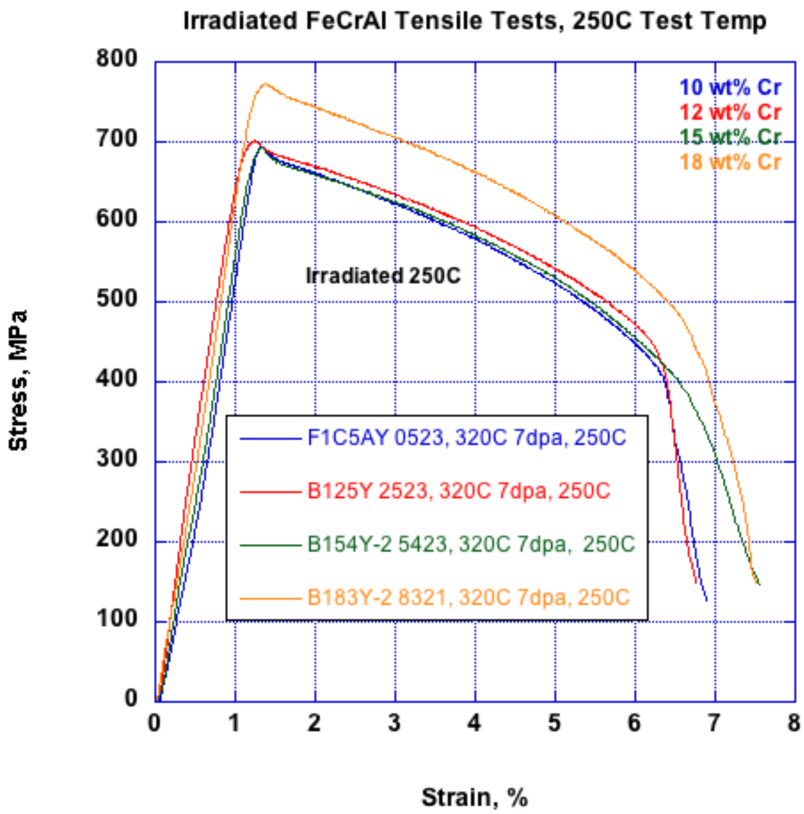

Figure 8 *Elevated temperature (250℃) tensile tests of irradiated (320℃ 7dpa) GenI FeCrAl alloys.*

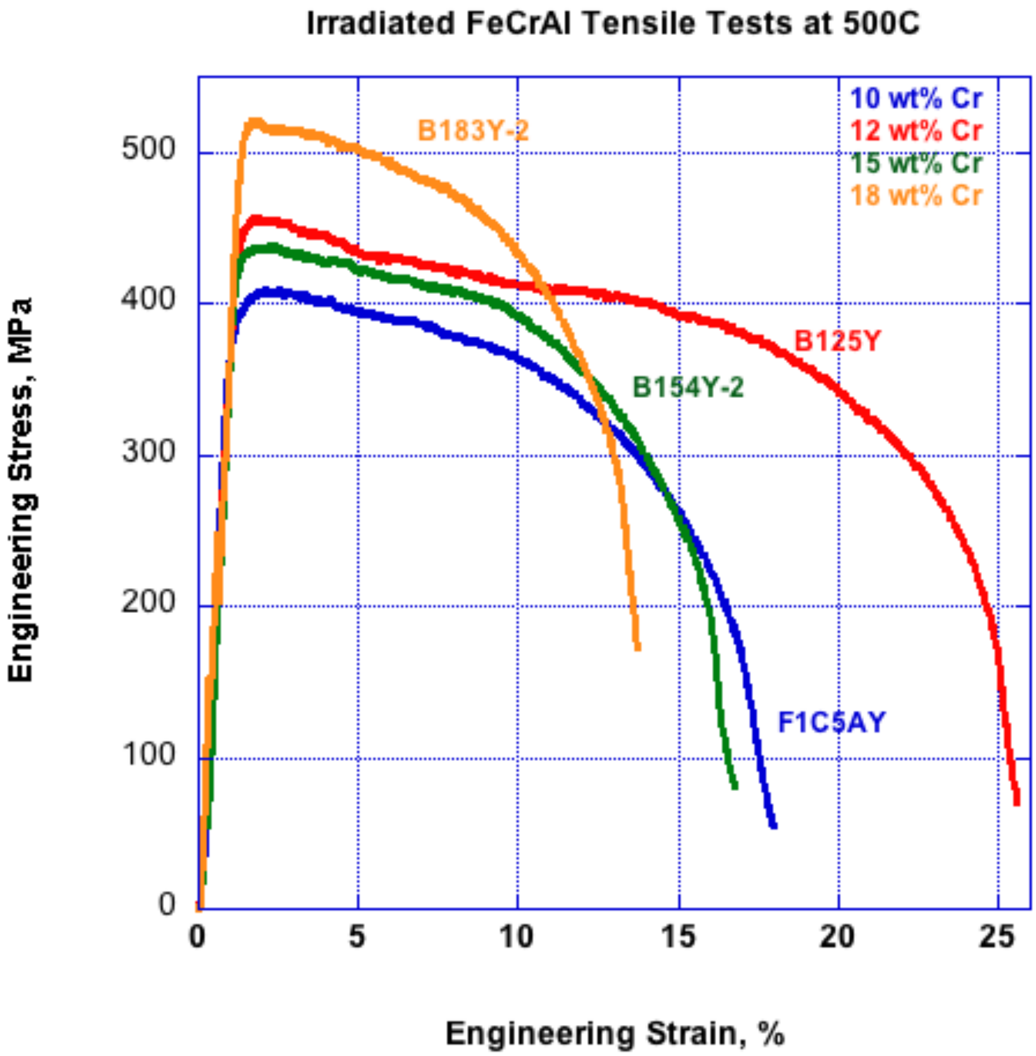

Figure 9 *Elevated temperature (500°C) tensile tests of irradiated (320°C 7dpa) GenI FeCrAl alloys*

The GenII alloys control tensile tests at room temperature and 250°C are shown in Figure 10. The control data is fairly similar between the two alloys. There is a much higher elongation for the "B" samples which are aligned with the tensile axis in the rolling direction, than in the "A" samples that are aligned perpendicular to the rolling direction. The yield strength and initial strain hardening are fairly similar for both orientations, but the uniform elongation and total elongation are 20-80% more for the rolling direction samples. The ultimate tensile strength also is higher in the "B" samples. Both testing directions in both alloys provided better mechanical behavior in terms of ductility than the similar control GenI alloys.

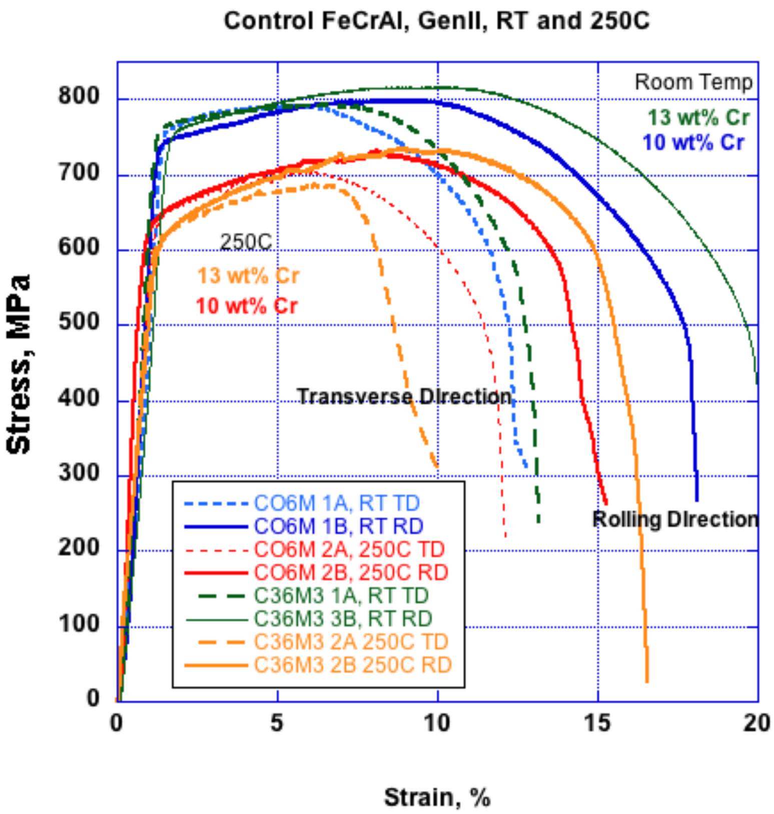

Figure 10 *Room and elevated temperature (250℃) tensile tests of control GenII FeCrAl alloys.*

5. Conclusions and Future Work

The mechanical tests performed for this report show very low ductility and increased hardening for GenI FeCrAl alloys irradiated to 7dpa at 320°C and tested at room temperature, 250°C and 500°C. This is consistent with previous tests of this same irradiation tested at room temperature and 320°C. Based on microstructural studies, the irradiation induced α' formation has a large effect on the hardening of these alloys. Initial mechanical tests at room temperature and 250°C of the control GenII FeCrAl alloys were also performed. These materials had much more ductile behavior in the unirradiated state than the GenI alloys.

Future work will entail performing shear punch tests on the undeformed grip of the room temperature tested irradiated GenI FeCrAl tensile samples. This will provide a baseline shear to tensile property-property relationship for these materials. Additional microstructural analysis including TEM and SANS for the alloys in these conditions will continue. For the GenII alloys, more control tests will take place at elevated temperature, up to 500°C, to provide comparison data for future analysis of the same alloys from the FCAB/FCAT HFIR irradiation.

6. References

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